GOATS 2005
Integrated, Adaptive Autonomous Acoustic Sensing Systems

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LONG-TERM GOALS

To develop net-centric, autonomous underwater vehicle sensing concepts for littoral MCM and ASW, exploiting collaborative and environmentally adaptive, bi- and multi-static, passive and active sonar configurations for concurrent detection, classification and localization of proud and buried targets.

OBJECTIVES

The objective of the continuing GOATS interdisciplinary research program is to develop, implement and demonstrate real-time, onboard integrated acoustic sensing, signal processing and platform control algorithms for adaptive, collaborative, multiplatform REA, MCM, and ASW in unknown and unmapped littoral environments with uncertain navigation and communication infrastructure.

A rellated objective is the development of a nested, distributed command and control architecture that enables individual network nodes of clusters of nodes to complete the mission objectives, including target detection, classification, localization and tracking (DCLT), fully autonomously with no or limited communication with the network operators. The need for such a nested, autonomous communication, command and control architecture has become clear from the series of experiments carried out in the past under GOATS and several recent experiments carried out under the UPS PLUSNet program.

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APPROACH

The GOATS (Generic Ocean Array Technology Sonar) research program is a highly interdisciplinary effort, involving experiments, theory and model development in advanced acoustics, signal processing, and robotics. The center-piece of the research effort has been a series of Joint Research Projects (JRP) with SACLANTCEN. The joint effort was initiated with the GOATS' 98 pilot experiment [1] and continued with the GOATS' 2000 and BP02/MASAI02 experiments. Currently the collaboration is being continued under a NURC JRP on sensing network technology. In addition to the field experiments involving significant resources provided by NURC, GOATS uses modeling and simulation to explore the potential of autonomous underwater vehicle networks as platforms for new sonar concepts exploring the full 3-D acoustic environment of shallow water (SW) and very shallow water (VSW).

The fundamental approach of GOATS is the development of the concept of a network of AUVs as an array of *Virtual Sensors*, based on fully *integrated sensing, modeling and control*, reducing the inter-platform communication requirements to be consistent with the reality of shallow water acoustic communication in regard to low bit-rate, latency and intermittency. Thus, for example the past GOATS effort has demonstrated that platform motion information can be used for clutter control by providing geometric constrains to on-board detection algorithms, reducing the communication requirements to location, POD, and classification information. Conversely, on-board sensor fusion and processing can be fed back to the vehicle control system for autonomous, adaptive sampling – again with the potential for significantly enhanced POD/PFA performance.

In regards to applications to MCM, GOATS explores the use of bi-static and multi-static Synthetic Aperture created by the network, in combination with low frequency (1-10 kHz) wide-beam insonification to provide coverage, bottom penetration and location resolution for concurrent detection, localization and classification of proud and buried targets in SW and VSW. The signal processing effort is therefore centered around generalizing SAS processing to bi-static and multi-static configurations, including bi-static generalizations of auto-focusing and track-before-detect (TBD) algorithms. Another issue concerns the stability and coherence of surface and seabed multiples and their potential use in advanced low-frequency SAS concepts.

More recently, the GOATS effort has transitioned towards the development of similar, autonomous network concepts for passive littoral surveillance, e.g. the Undersea Persistent Surveillance (UPS) program, initiated in 2005 and completed in 2008. PI Schmidt was lead PI and Chief Scientist for the UPS PLUSNet Program, which developed a network concept of operations based on clusters of AUV and gliders, connected via acoustic communication, and intermittent RF communication with the operators through periodically surfacing gliders. A prototype network concept with a hybrid, cooperating suite of underwater and surface assets was successfully demonstrated in PN07 in Dabob Bay, WA. The MIT UPS effort is curretly being transitioned into the ONR PLUS INP. As in the past GOATS effort, the MIT marine autonomy effort is utilizing the open-source MOOS control mission control software originally developed and funded under GOATS. However, in contrast to past experiments where all platforms were controlled and piloted by MIT, the PLUSNet concept demonstrated the feasibility of ahybrid suite of diverse network nodes, with significant native, proprietary, software infrastructure. To take advantage of the robustness of the native control software, while at the same time retaining the flexibility in regard to sensor-driven adaptivity and collaboration, MIT, and in turn PLUSNet, has adopted a new nested control architecture, where the lower level

control of the nodes, as well as the overall field control can be performed using arbitrary third-party software, while the medium level, adaptive and collaborative control of the nodes and the clusters is performed within the MOOS software framework.

Such a nested command and control infrastructure with heterogeneous assets invariably need translation to and from a common communications protocol. Starting with the MB'06 experiment, MIT and Bluefin AUVs were controlled using a new, so-called “back-seat driver” paradigm wherein low-level commands to the Bluefin control software were translated and conveyed by a specially designed MOOS module.

The mid-level, adaptive and collaborative control of the network nodes is carried out using MOOS in combination with the new multi-objective, behavior-based IvP control framework developed within MOOS by Michael Benjamin at NUWC/MIT. The core of this architecture consists of a behavior-based control system which uses multiple objective functions to determine the appropriate course, speed, and depth of the platform at every control cycle (typically 10-20 Hz). The desired course of action is determined by computing a multi-function optimization over the objective functions using the Interval Programming Model developed by Benjamin [5] which provides a very fast optimization suitable for small vehicles.

The development of GOATS concepts, including PLUSNet, is based heavily on simulation, incorporating and integrating high-fidelity acoustic modeling, platform dynamics and network communication and control. In regard to the environmental acoustic modeling, MIT continues to develop the OASES-3d modeling framework for target scattering and reverberation in shallow ocean waveguides. As has been the case for the autonomous command and control, recent emphasis has been towards the simulation of passive DCLT by the PLUSnet network. As was previously the case for the MCM effort, the approach has been to develop a complete system simulation capability, where complex adaptive and collaborative sensing missions can be simulated using state-of-the-art, high-fidelity acoustic models for generating synthetic sensor signals in real time. As in the past, this has been achieved by linking the real-time MOOS simulator with the SEALAB acoustic simulation framework, which in ‘real-time’generates element-level timeseries using Green’s functions using legacy environmental acoustic models such as OASES, CSNAP, and RAM. This new unique simulation environment allows for full simulation of adaptive DCLT missions for the MIT/Bluefin AUVs towing hydrophone arrays, incorporating correlated and directional ambient noise, and signals generated by moving surface ships and targets

WORK COMPLETED

Nested, Distributed Autonomous Communication, Command and Control Architecture

The FY08 effort has focused on a significant expansion of the MOOS-Ivp autonomy software suite to support the rapidly growing application community. In addition a structure, nested repository has been established at MIT, in collaboration with NUWC, which allows the various user communities to share a large percentage of the processing and control modules. The robustness and versatility of the MOOS-IvP autonomy architecture was demonstrated in the GLINT08 experiment, carried out in collaboration with NURC near the island of Pianosa, Italy, in August 2008. Here several underwater vehicles and shore-based cabled bottom nodes were all being operated using the same MOOS-IvP autonomy system, and a common communication infrastructure based on the WHOI micromodem.

A major accomplishment in this regard is the development of a new MOOS-IvP Autonomous Communication, Command and Control software stack. Collaborative AUV missions require robust and sufficient data throughput (e.g. tracking data, environmental data, pose information). Research demands rapidly prototyping; in the context of acoustic communications, it should be possible to create and send a new message type on short notice without disrupting the existing communications infrastructure. Furthermore, given the limitations of the acoustic communication channel, significant effort must be made to compress data on the software level before transmission.

We redesigned the MOOS-IvP acoustic networking stack to further these objectives. The old networking stack only supported the lowest rate message of the WHOI MicroModem (eighty bits per second (bps)) and was inflexible: writing a new message type or changing the command set required modifying legacy code, which always carries a high risk of disruption.

The new networking stack introduces a new message queuing process, pAcommsHandler. This process dynamically prioritizes messages based on last send time, weighted by base priorities depending on the importance of the message. For example, target track messages are given a high base priority while status messages are given a low priority. Thus, track messages (when available) are sent most often, but eventually the priority of the status message will grow high enough to get a message through to give the vehicle operators periodic information about the vehicle's status. This interleaving can be used for an arbitrary number of message types. Equally importantly, new message types can be added with only minor disruption to the queuing of old message types. Acoustic acknowledgments are now supported for messages in the new stack, allowing for a more robust command infrastructure. Finally, pAcommsHandler allows the user to take advantage of the high rate phase shift keying (PSK) messages, allowing throughput of up to 5400 bps.

The second major change is a paradigm shift from encoding / decoding messages in a single process towards a suite of codecs. This paradigm is based on the MOOS idea that individual processes should never interact with each other, only the central database. Similarly, individual codecs should never interact with each other. This allows a developer to create a custom message encoding scheme without knowing or disrupting existing schemes.

Two new codecs were developed and tested. A CTD codec (pCTDCodec) was coded to take environmental data and define a highly compact custom message based on the operating conditions. This style of encoding allows for significantly more compressed messages than "static" encoding schemes, such as traditional Compact Control Language (CCL). A codec that takes tracking data from the beam former for the DURIP acoustic array was written and tested, allowing bearing track record (BTR) data to be available topside in near real time during operations. All the message rates were tested in the new system, allowing up to a sixty-fold increase in data throughput over the old communications stack.

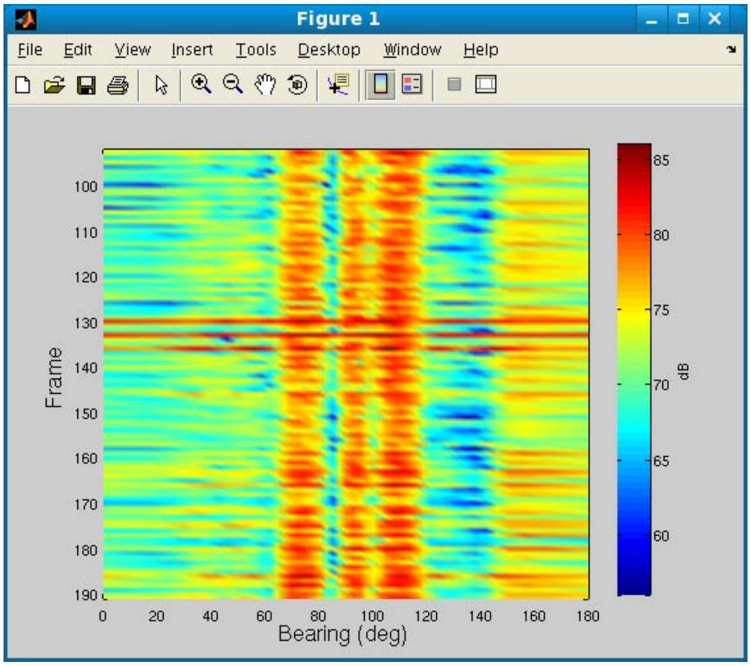


Figure 1 Real-time topside display of BTR data transmitted from Unicorn BF21 using new PSK message structure during joint NURC/MIT GLINT08 experiment.

Backseat Driver Paradigm

In FY06, MIT developed a new, portable backseat-driver control architecture to allow the low-level vehicle control to be handled by the native control software, while the higher level adaptive control can be performed using the behavior-based MOOS-IvP software architecture. The concept defines a set of NMEA commands to handle the communication between the two control softwares, with MOOS-IvP producing commands for desired speed, depth and heading, which the native software translating these into actuator commands, and returning status information and navigation data to the higher level (back-seat deriver) control. As part of the joint effort with NURC, the MOOS-IvP backseat driver concept was adopted and implemented in the NURC Ocean Explorer AUV, making it fully operational compatible with the MIT BF21 vehicles, as demonstrated by the collaborative multistatic active missions carried out in GLINT08. It was also adapted successfully to the NURC FOLAGA environmental sampler.

MOOS-IvP Surveillance Network Simulator

The development of the robust and efficient processing algorithms and autonomous, adaptive and collaborative behaviors at the core of GOATS, it crucial to the effective use of at-sea time and resources, to have available a comprehensive simulation environment. With its modular structure, composed of individual processes communicating through a central database, MOOS is inherently capable of being run in simulation mode in a configuration that is arbitrarily close to the configuration running the actual missions. Thus, the simulation can be performed on the actual vehicle computer or a separate laptop or desktop, with some of the hardware in-the-loop, such as acoustic modems. Also, the simulator has a Matlab interface, which allows new processing algorithms and behaviors to be developed interactively in Matlab, and then later compiled into true, real-time MOOS processes. .

In support of the UPS and PLUS programs, and the joint effort with NURC in GLINT, capability is the addition of a MOOS module, iModemSim, for high-fidelity simulation of a network of WHOI Micromodems. This simulator incorporates probability of correct message reception, collisions, and transmission latencies. As such this new capability allow simulation of complex collaborative and adaptive missions of multiple vehicles with realistc modem communication performance, all on a single computer without dedicated modem emulation hardware.

Another addition to the simulator is the capability of handling multiple sources, allowing the simulator to be applied for exercising DCLT in high-clutter environments.

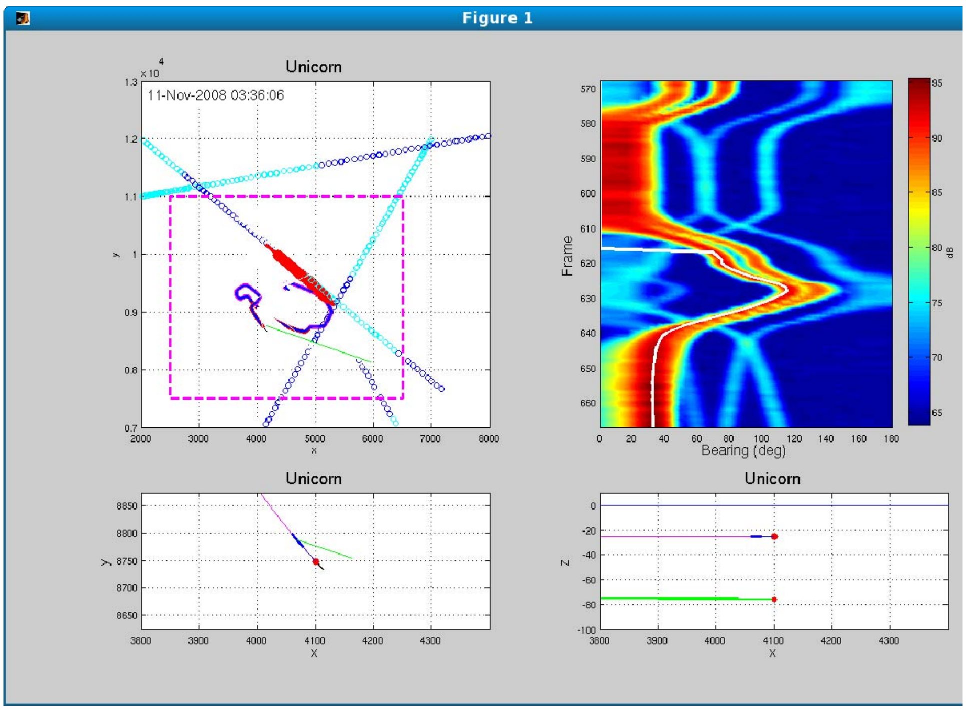


Figure 2. MIT MOOS-IvP simulation of adapotive prosecution of a moving acoustic source in a high-clutter environment. Upper left shows area map with targets and interferer tracks indicated with cyan and

Figure 2 shows an example of a simulation experiment performed using the new simulation capability. A BF21 AUV with towed array is performing an adaptive maneuver for generating a track solution for a moving target in the presence of several interferers. The source is here a high-SNR contact, because the signal processing is here performed using a simple beamformer and detector.

3-D Normal Mode Model for Scattering around Conical Seamount

The three-dimensional coupled-mode model that has been developed under this project [3], has been optimized for accuracy and speed of the computations. Further, it has been prepared for implementation on massively parallel computers at MIT and Lincoln Laboratories for generating time-domain solutions to be applied for analysis of the data collected at the Kermit seamount under the NPAL program. In addition it has been applied to analyze dependence of 3-D effects on slope of seamounts and an extensive analysis has been performed in regard to the physics of mode coupling in 3-D seamount problems.

RESULTS

3-D Propagation and Scattering around Conical Seamounts

Dependence of 3-D effects on slope of seamounts

We have considered the canonical problem shallow water seamount problem shown in Fig. 3. Results of transmission loss in the horizontal plane at depth 100 m with height of seamount as 100 m and 200 m are shown in Fig. 4, from which it can be seen that as the slope of seamounts increases, 3-D effects become more significant. Also, these results as well as the modelings performed for the deep water Kermit seamount show that the most significant 3-D effect is a ‘deepening’ of the shadow zone behind the seamount.

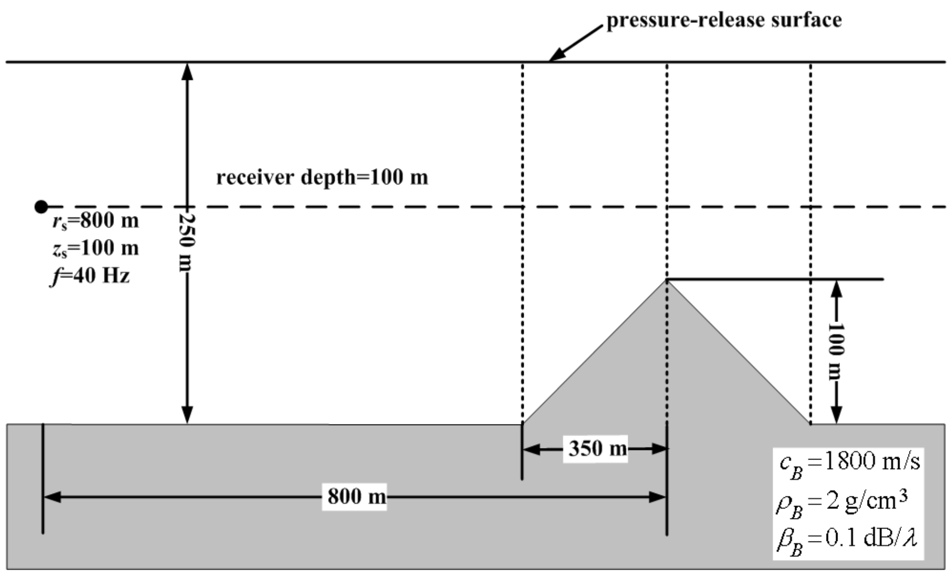


Figure 3. A seamount problem used to illustrate the dependence of 3-D effects on slope of seamounts. The height of seamount in this problem is 100 m or 200 m.

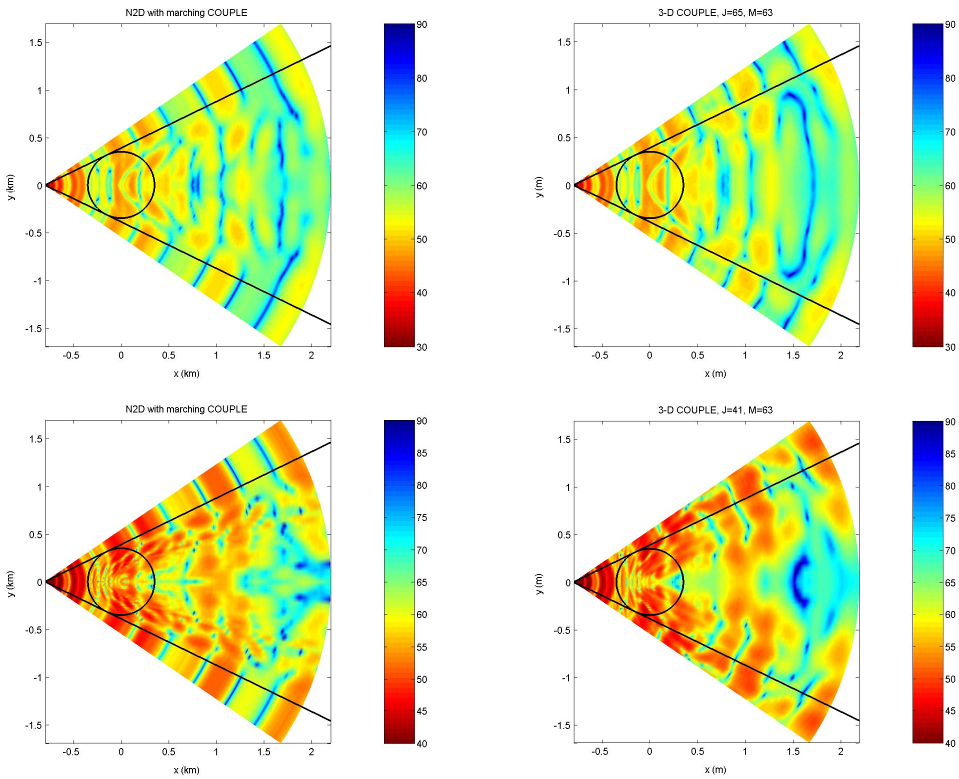


Figure 4. Transmission loss in the horizontal plane at depth 100 m. The above two figures are computed by N2D and 3-D models with height of seamount of 100 m; the below two figures are computed by N2D and 3-D models with height of seamount of 200 m.

3-D Mode coupling by conical seamount

In the present model, the scattered field in the external region of a seamount is

$$p_s(r,z,\varphi) = \sum_{m=0}^{\infty}\sum_{n=1}^{\infty} a_{mn}^{J}\hat{H}_m^{(1)}(k_{rn}^{J}r)\Psi_n^{J}(z)\Phi_m(\varphi)$$

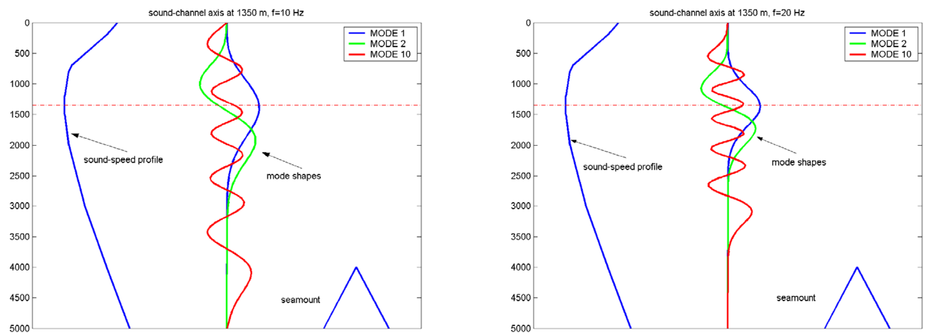
$$= \sum_{n=1}^{\infty}\left[\sum_{m=0}^{\infty} a_{mn}^{J}\hat{H}_m^{(1)}(k_{rn}^{J}r)\Phi_m(\varphi)\right]\Psi_n^{J}(z),$$

and mode amplitudes are defined as

$$A_n(\varphi) = \sum_{m=0}^{\infty} a_{mn}^{J}\Phi_m(\varphi).$$

It is clear that for an individual incident mode to excite a non-vanishing scattered field, the oscillating region of this mode must extend to a depth below the summit of the seamount, in which case strong 3-D mode coupling occurs. Otherwise, the propagation of this incident mode is not affected by the seamount.

As an example, we consider a seamount of height 1000 m, in a waveguide deep water with sound axis at depth 1350 m. As the source frequency is 10 Hz, the oscillating region of mode 10 extends to the bottom, as shown in Fig. (5a), leading to strong mode coupling at the edge of the seamount; as the source frequency is 20 Hz, the oscillating region of mode 10 is above the summit of the seamount, as shown in Fig. (5b), so the propagation of this mode is not affected by the seamount and the scattered field is zero. Fig. 6 shows contours of the scattered mode amplitudes versus azimuthal angle (0 is forward scatter, 180 backscatter) and mode number. Th incident mode is mode 10 in this case10. As observed, mode coupling is significant not only in the vertical, but also in azimuth.



(a) (b)

Figure 5. Mode shapes in the external region of the seamount. The height of seamount is 1000 m, (a) source frequency is 10 Hz, (b) source frequency is 20 Hz.

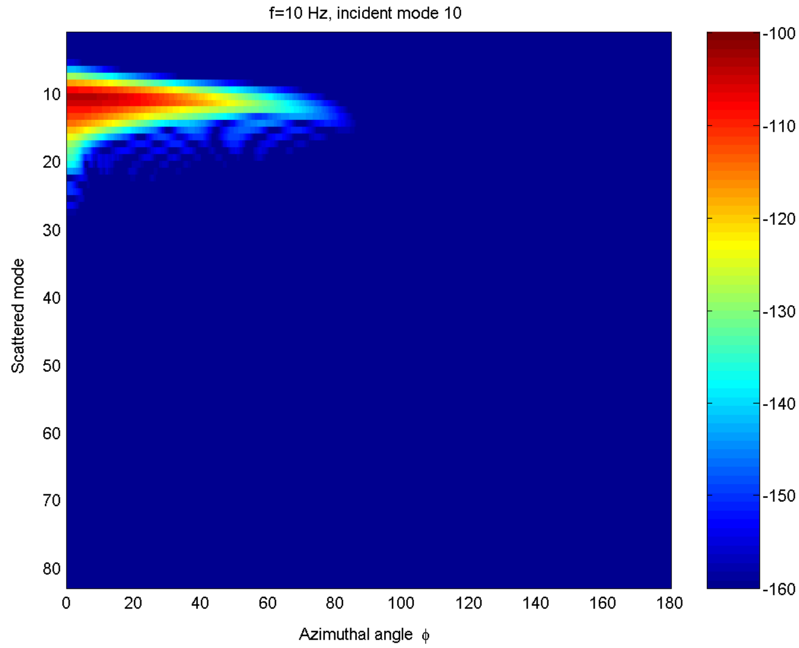


Figure 6. Mode amplitudes with mode 10 incident on the seamount, the source frequency is 10 Hz.

IMPACT/APPLICATIONS

The long-term impact of this effort is the development of new sonar concepts for MCM and ASW, which take optimum advantage of the mobility, autonomy and adaptiveness of an autonomous, cooperating vehicle network. For example, bi- and multi-static, low-frequency sonar configurations are being explored for completely or partially proud or buried mines in shallow water, with the traditional high-resolution acoustic imaging being replaced by a 3-D acoustic field characterization as a combined detection and classification paradigm, exploring spatial and temporal characteristics which uniquely define the target and the reverberation environment. Similarly, platform mobility and collaboration is being explored for enhancing DCLT performance of littoral surveillance networks such as PLUSNet.

TRANSITIONS

The progress made in autonomous, multi-AUV, net-centric control, navigation, communication, and collaborative sensing and its implementation into the MOOS-IvP autonomy system architecture, has been transitioned into the ASAP-MURI and the now completed Undersea Persistent Surveillance (UPS) PLUSNet effort for which PI Schmidt was Lead-=PI and Chief Scientist.

Further, the MOOS-IvP software architecture (MOOS was originally developed by P. Newman under GOATS funding in 2002) is being transitioned to the ONR UCII program, as well ast the new PLUS INP distributed surveillance program, where it has been chosen at the autonomy system baseline, from which it will be be developed into a restricted or classified MOOS-IvP+ software repository, established in collaboration between NUWC and MIT Lincoln Laboratories.

Finally, MOOS-IvP is being transitioned to handle the Mission Planning and Control of both moving and fixed assets in the NSF ORION Ocean Observatories. Thus MIT is partner in the UCSD led team charged with developing the Cyber Infrastructure for ORION, with responsibility for the MP&C.

The seismo-acoustic models developed by MIT are being maintained and dissiminated under the GOATS grant. The OASES and CSNAP environmental acoustic modeling codes are used extensively in the ONR sponsored r5esearch at MIT, and continue to be maintained, expanded and made available to the community. The latest addition is a 3D version of CSNAP, which efficiently provides wave-theory solutions for propagation and scattering around seamounts. OASES and CSNAP is continuously being exported or downloaded from the OASES web site, and used extensively by the community as a reference model for ocean seismo acoustics in general. (http://acoustics.mit.edu/arctic0/henrik/www/oases.html) Among the new transitions to applied Navy programs, the OASES and CSNAP framework is being used extensively by several contractors such including Lockheed-Martin, BBN, Northrop-Grumman, and SAIC., and Navy laboratories, including NUWC, NURC, CSS, and NRL.

RELATED PROJECTS

This effort has constituted part of the US component of the GOATS`2000 Joint Research Project (JRP) with the SACLANT Undersea Research Centre, and is currently collaborating with NURC under the Autonomous Sensing Networks Joint Research Projects (JRP). The MIT GOATS effort has been funded jointly by ONR codes 321OA (Livingston), 321OE (Swean,Curtin), and 321TS (Johnson/Loeffler/Commander).

The GOATS program developed out of the ONR Autonomous Ocean Sampling Network (AOSN) initiative completed in FY00, and is strongly related to the continuing AOSN effort. GOATS is also directly related to the Shallow Water Autonomous Mine Sensing Initiative (SWAMSI), initiated in FY04, and currently continuing, and of which MIT is a partner.

The adaptive command and control architecture and acoustic modeling capabilities developed under GOATS are being applied in several other related programs MIT is partnering in, including the AREA (Adaptive Rapid Environmental Assesment) component of the now completed ONR “Capturing Uncertainty” DRI, aimed at mitigating the effect of sonar performance uncertainty associated with environmental uncertainty by adaptively deploying environmental assesment resources. The cooperative AUV behavior progress together with the AREA concept is being currently transitioned into the ASAP MURI and the Undersea Persistent Surveillance (UPS) program, with experimental demonstrations in Monterrey Bay in MB06 and in Dabob Bay, WA in PN07.

The OASES modeling framework, which is being maintained, upgraded, and distributed to the community under this award, has been used intensively in all the related programs MIT is participating in. The new 3D model of propagation over seamounts [3] is being transitioned and applied to the analysis of the experimental results obtained at Kermit seamount under the NPAL program.

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